Shedding Light on High T_c Superconductivity

Atomic Vibrations Shown to be Involved

A team of researchers in the U.S. and Japan led by MSD physicist Alessandra Lanzara has produced the first direct evidence of "a significant and unconventional" role in high temperature superconductivity for phonons, the vibrations of the atoms that form the superconductor's crystalline lattice.

Superconductivity is a state in which a material loses all electrical resistance. Once established, an electrical current will flow forever. Many metals superconduct, but only at temperatures very close to absolute zero. The physics behind this low-temperature superconductivity has been successfully explained by BCS theory, named for its Nobel-prize winning authors, John Bardeen, Leon Cooper, and Robert Schrieffer. According to BCS theory, superconductivity arises when electrons, which naturally repel one another because of their mutual negative charge, come together to form "Cooper pairs." Cooper pairing cancels out any disruption in the flow of an electrical current caused by crystal impurities, a source of electrical resistance. Electrons are able to pair up because one of them interacts with a phonon, creating what can be thought of as an atomic sound wave. The second electron is affected by this alteration, as a ship passing through another's wake.

High temperature superconductivity, which was discovered in the 1980s in doped copper oxides, or cuprates, has been thought to be fundamentally different; the prevailing scientific thought has been that electron-phonon coupling plays little or no role in superconductivity in these materials. The Lanzara group took a critical look at this hypotheses by performing a unique experiment on the ALS undulator beamline 10.0.1, using a technique called angle-resolved photoemission spectroscopy (ARPES). In ARPES, monochromatic x-ray light is flashed on a sample, causing electrons to be emitted through the photoelectric effect. Subsequent measurement of the kinetic energy of the emitted electrons and the angles at which they are ejected enables the determination of the binding energy of the material's electrons as a function of their momentum. Simultaneous measurement of energy and momentum, known as an electron's dispersion relation, yields valuable information about electron interactions within the sample.

For their experiments, Lanzara and her colleagues replaced some of the normal oxygen-16 in Bi-2212, a cuprate doped with bismuth, strontium and calcium that becomes superconducting at 92 K, with a heavier isotope, oxygen-18, and then compared ARPES measurements. Beamline 10.0.1 provides a high enough degree of angular and energy resolution that they could determine the small differences in electron dynamics resulting from a crystal lattice made heavier and stiffer by the oxygen-18 substitution. In a comprehensive study, the group measured the dispersion relations for electrons that contributed to superconductivity and also for those that did not. They found that for certain electrons involved in superconductivity, the dispersion curves for the oxygen-18 substituted materials were different – clear evidence of the involvement of phonons in the superconducting mechanism (if phonons were not involved, changes in the masses of the atoms in the atomic lattice would have had no effect).

The group further deduced that in high-temperature superconductors like Bi-2212, phonons stabilize the Cooper pairing of electrons in a process triggered by "antiferromagnetism." The antiferromagnetism arises when the magnetic spins of electrons in the lattice align themselves with neighboring spins pointing in opposite directions. In a qualitatively new explanation for explaining high temperature superconductivity, they propose that the formation of the Cooper pair is mediated through the phonons, while at the same time, there is a feedback from the anti-ferromagnetic interaction. Thus the two phenomena enhance one another.

A. Lanzara (510)642-4863, Materials Sciences Division (510 486-4755), Berkeley Lab.

G.-H. Gweon, T. Sasagawa, .Y. Zhou, J. Graf, H. Takagi, D.-H. Lee& A. Lanzara, "An unusual isotope effect in a high-transition-temperature superconductor," *Nature* **430**, 187 (2004).